PICSC – FINAL REPORT

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PROJECT TITLE: Development of Statistical Methods to Estimate Baseline and Future Low-Flow Characteristics of Ungaged Streams in Hawai‘i

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2. PUBLIC SUMMARY

Climate change will affect the beneficial uses of streamflow, which include supplying freshwater for irrigation and domestic needs, providing for traditional and customary Hawaiian practices, and maintaining habitat for native stream fauna. Statistical models were developed to estimate surface-water availability during low-flow conditions for varying rainfall conditions. Results of this study include a spatial understanding of changes in low flows and usable stream habitat on Maui for a range of projected rainfall conditions for the late 21st century. This analysis indicates that stream responses to rainfall vary spatially in Hawai‘i. For example, a 10-percent decrease in rainfall may result in a 7% decrease in low flows in West Maui streams, compared to a 20-percent decrease in low flows in East Maui streams. The simple models developed for this study are appropriate for regional climate-change impact assessments given the available data and uncertainty in climate projections. The methods developed for this study are transferable to other Pacific islands as well as continental settings.

3. TECHNICAL SUMMARY

Multicollinearity and omitted-variable bias are major limitations to developing multiple linear regression models to estimate streamflow characteristics in ungaged areas and varying rainfall conditions. Panel regression is used to overcome limitations of traditional regression methods, and obtain reliable model coefficients, in particular to understand the elasticity of streamflow to rainfall. Using annual rainfall and selected basin characteristics at 86 gaged streams in the Hawaiian Islands, regional regression models for three stream classes were developed to estimate the annual low-flow duration discharges. Three panel-regression structures (random effects, fixed effects, and pooled) were compared to traditional regression methods, in which space is substituted for time. Results indicat that panel regression generally was able to reproduce the temporal behavior of streamflow and reduce the standard errors of model coefficients compared to traditional regression, even for models in which the unobserved heterogeneity between streams is significant and the variance inflation factor for rainfall is much greater than 10. This is because both spatial and temporal variability were better characterized in panel regression. In a case study, regional rainfall elasticities estimated from panel regressions were applied to ungaged basins on Maui, using available rainfall projections to estimate plausible changes in surface-water availability and usable stream habitat for native species. The presented panel-regression framework is shown to offer benefits over traditional hydrologic regression methods for developing robust regional relations to investigate streamflow response in a changing climate.

4. PURPOSE AND OBJECTIVES

Potential effects of climate change on low flows in Hawai‘i streams need to be better understood to properly manage surface-water resources. The objectives of this study were to

1. compute baseline low flows for gaged sites in Hawai‘i,
2. develop statistical methods to estimate natural low flows at ungaged sites for current rainfall conditions, and
3. evaluate the applicability of the developed statistical methods to estimate natural low flows for future rainfall conditions.

Methods are illustrated in a case study. This study estimated changes in natural low flows for gaged and ungaged streams on the island of Maui and associated impacts on habitat area for native aquatic fauna using available downscaled climate projections for the late 21st century.

All three objectives of this study were met and results for the case study were prtesented. Results associated with objective 1 and the case study were provided as project deliverable in published spreadsheets (Bassiouni, 2016). Objectives 2 and 3 are presented and discussed in Bassiouni et al. (in press).

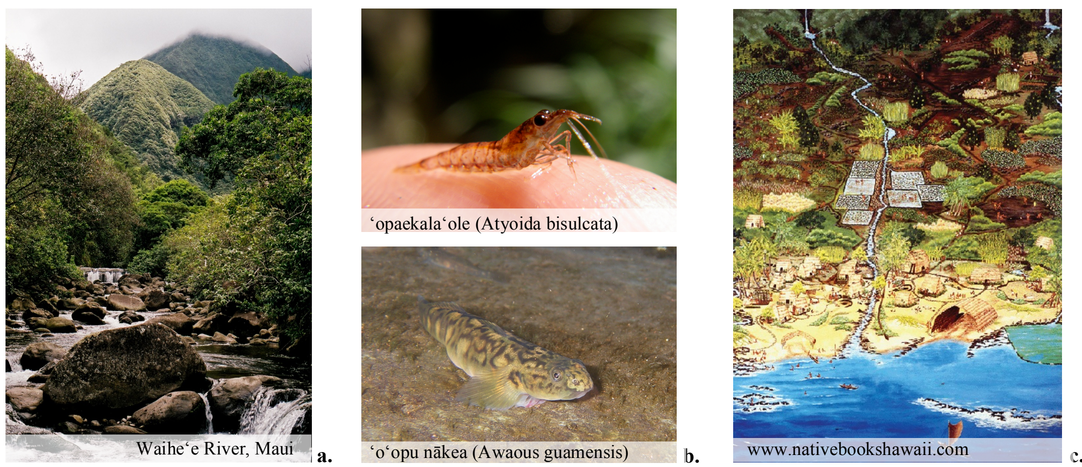

Figure 1. Climate change affects the beneficial uses of streamflow in Hawai‘i including (a) freshwater for irrigation and domestic uses, (b) habitat for native stream species, and (c) traditional and customary Hawaiian rights.

5. ORGANIZATION AND APPROACH

Streamflow, climate, soil, morphometric, and land-cover characteristics were computed and compiled for gaged basins that met the selection criteria in this study. A base period to estimate low flows for current conditions was initially proposed. Instead, the analysis was conducted on annual streamflow-rainfall pairs of up to 30 consecutive water years. This approach was modified because:

- the number of gaged basins with long-term concurrent streamflow records was insufficient,
- record-extension methods create correlation between records and may not be appropriate in this study, and
- annual values provide a greater range of variability necessary to develop models for a larger range of rainfall conditions..

Methods to develop multiple linear regression (MLR) models to estimate current and future low flows in ungaged streams were evaluated. Ordinary least-squares and weighted least-squares methods (traditional methods) were initially proposed to estimate low flows. Instead, this study used panel-regression methods to develop MLR models to estimate annual low flows as a function of annual rainfall and static physical basin characteristics. Panel regression is a more robust alternative for climate-change studies because:

- the use of traditional regression methods with correlated explanatory variables may create highly sensitive parameter estimators and improper model selection (multicollinearity),
- for cases in which a MLR leaves out important causal factors and is developed using traditional methods, the effect of these factors is compensated by over- or underestimating the effect of other explanatory variables (omitted-variable bias), and these effects are magnified for small sample sizes,
- Panel regression accounts for within-basin (temporal), and between-basin (spatial) variability in the data, and therefore MLR coefficients estimated with panel-regression methods are more consistent and resulting models are more appropriate for future low-flow predictions.

MLR coefficients using panel-regression methods were fit using the package *plm* developed in the statistical computing language R.

Regions of similar streamflow sensitivity to changes in rainfall were determined and MLR models to estimate annual low flows (Q_{50}, Q_{70}, and Q_{90}) were developed for each region. Q_x represents the flow that is equaled or exceeded *x* percent of the time during the water year considered for a stream and is expressed as a daily mean discharge. Historical records for climatic variables such as temperature and evapotranspiration were not available for gaged sites in this study. These variables were not included in the MLR models and therefore projected changes in low flows only reflect the sensitivity of low flows to annual rainfall. The spatial variability of low flows is explained by both static physical basin characteristics and rainfall in the MLR models.

Developed models were applied using two sets of downscaled climate projections for the late 21st century to ungaged basins on Maui and estimates of changes in natural low flows and habitat area for native aquatic fauna were computed. Set A was derived from Coupled Model Intercomparison Project 5 (CMIP5) and the RCP8.5 scenario rainfall projections developed by Timm et al. (2015) and represents average annual rainfall anomalies for 2071-99 (Figure 2.A.). Set B was derived from CMIP3 and the A1B emission scenario developed by ADCP (2016) and represents average annual rainfall anomalies for 2090-2109 (Figure 2.B.). Changes in habitat area were estimated using relations developed by Oki et al. (2010).

6. RESULTS

Stream classification: Gaged sites were grouped into 4 classes (Figure 2):

- Non-perennial (*NP*)

Perennial stream with

- Low rainfall elasticity (P_l)
- Medium rainfall elasticity (P_m)
- High rainfall elasticity (P_h)

Rainfall elasticity (ε) is defined as the percentage change in low flow resulting from a percentage change in rainfall and was used to investigate the generalized sensitivity of annual low flows to changes in rainfall. A discriminant analysis was used to determine the stream class in ungaged areas on Maui (Figure 3).

Multiple linear regression (MLR) models: Random-effects panel regression was used to develop MLR models to estimate annual Q_{50}, Q_{70}, and Q_{90} discharges for each of the three perennial stream classes (Bassiouni et al., in press). Static basin characteristics selected in the nine MLR models included morphometric characteristics (drainage area; stream length; drainage density; average slope; basin relief) and surface-geology characteristics (percentage of area mapped as sedimentary rock; percentage of area mapped as shield-stage volcanics; percentage of area mapped as post-shield-stage volcanics; percentage of area mapped as rejuvenated-stage volcanics). Each model had a maximum of five basin characteristics. The MLR coefficient on rainfall is equal to rainfall elasticity (ε) and values for each stream class are summarized in Table 1.

Table 1. Rainfall elasticity (ε) values for stream classes (P_l, P_m, P_h) derived from random-effects panel regression.

Stream class	ε		
	Q_{50}	Q_{70}	Q_{90}
P_l	0.81	0.69	0.54
P_m	1.20	1.19	1.18
P_h	1.91	1.96	1.80

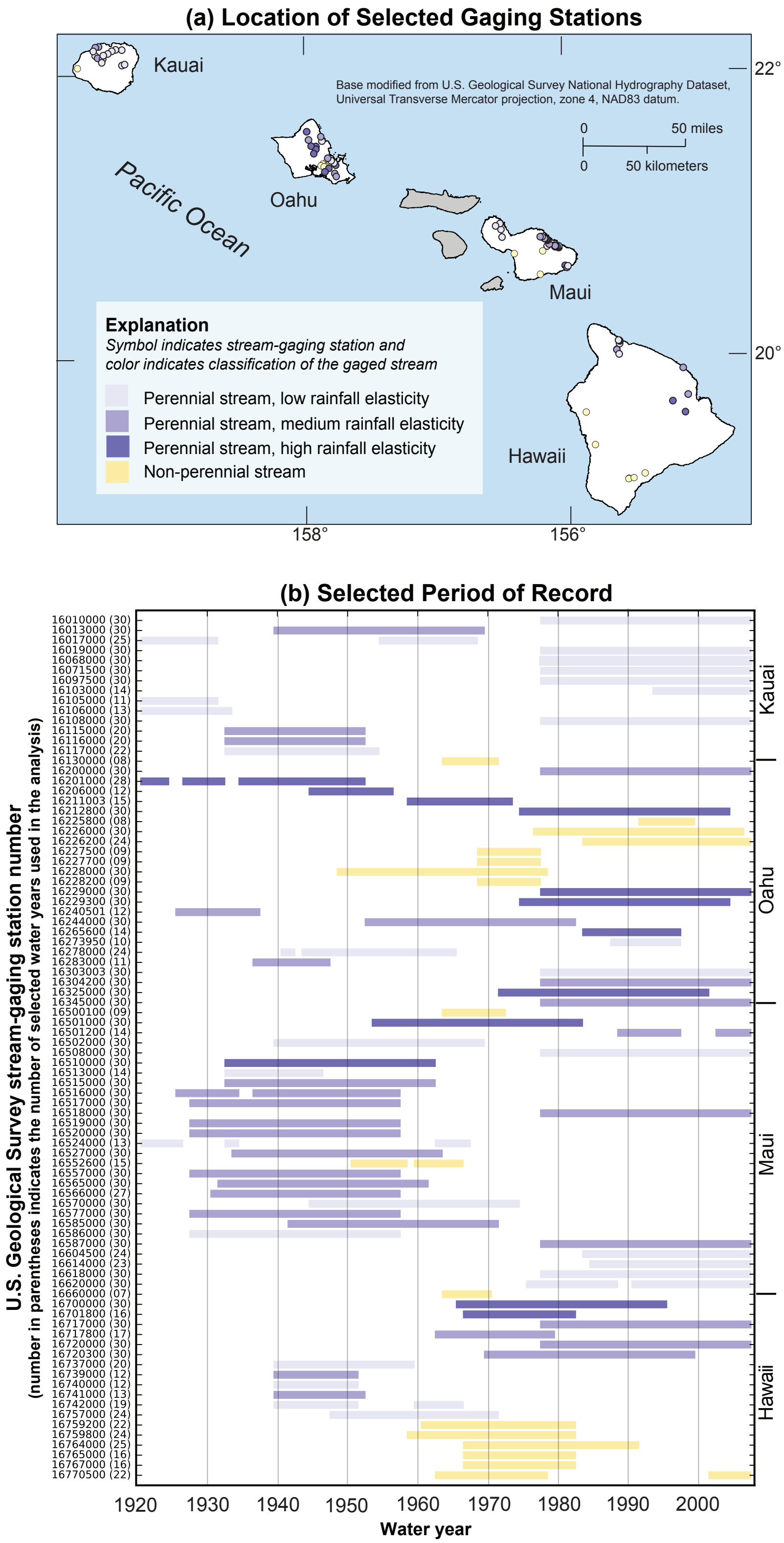

Figure 2. U.S. Geological Survey stream-gaging stations included in this study. (a) location and (b) periods of record analyzed in the regression analysis.

Maui Case study: The effect of climate change on low flows and stream habitat for native species in perennial streams on Maui are summarized in Table 2 and Figure 4.

Table 2. Median percentage change in rainfall from Timm et al., (2015) (A) and from ADCP (2016) (B), average annual low-flow duration discharges ($\overline{Q_{50}}$, $\overline{Q_{70}}$, $\overline{Q_{90}}$), and usable stream habitat area for native aquatic species (HA) in ungaged streams on Maui.

[P_l, perennial stream class with low rainfall elasticity; P_m, perennial stream class with medium rainfall elasticity; P_h, perennial stream class with high rainfall elasticity; *NP*, non-perennial stream class; *n*, number of ungaged stream points estimated; - , no low-flow and habitat-area estimates for non-perennial streams. Changes in low flows are computed using random-effects panel regressions]

Stream class	*n*	Percentage change in rainfall		Percentage change associated with indicated percentage change in rainfall							
				$\overline{Q_{50}}$		$\overline{Q_{70}}$		$\overline{Q_{90}}$		HA	
		A	B	A	B	A	B	A	B	A	B
P_l	91	-13	8	-11	6	-9	5	-7	4	-2	1
P_m	72	-1	18	-2	22	-2	22	-2	22	0	5
P_h	26	-6	15	-11	29	-11	30	-10	27	-3	6
NP	248	-48	-11	-	-	-	-	-	-	-	-

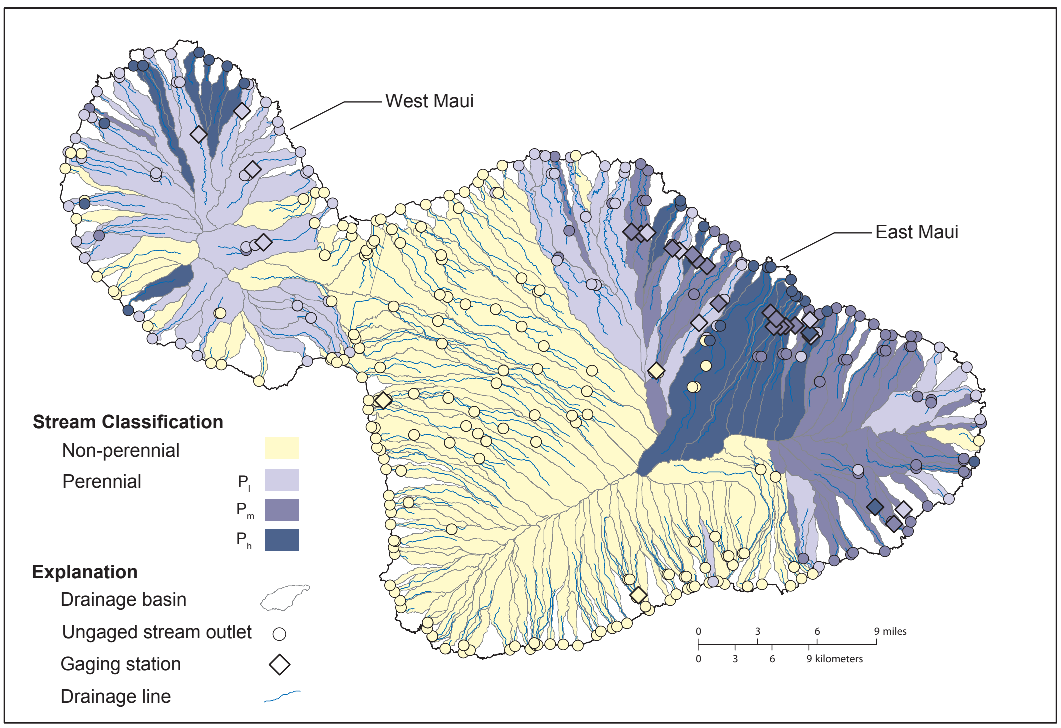

Figure 3. Classification of streams on the island of Maui estimated as a function of basin characteristics and annual rainfall for recent conditions using a linear decision function and classification of gaged stream (diamond) derived from streamflow and rainfall observations. Some ungaged streams may be misclassified. Shading of basins corresponds to the classification at the most downstream estimation point. Inland stream estimation points (circle) correspond to confluences of a stream network based on a 10-m DEM and a 20,000-cell threshold.

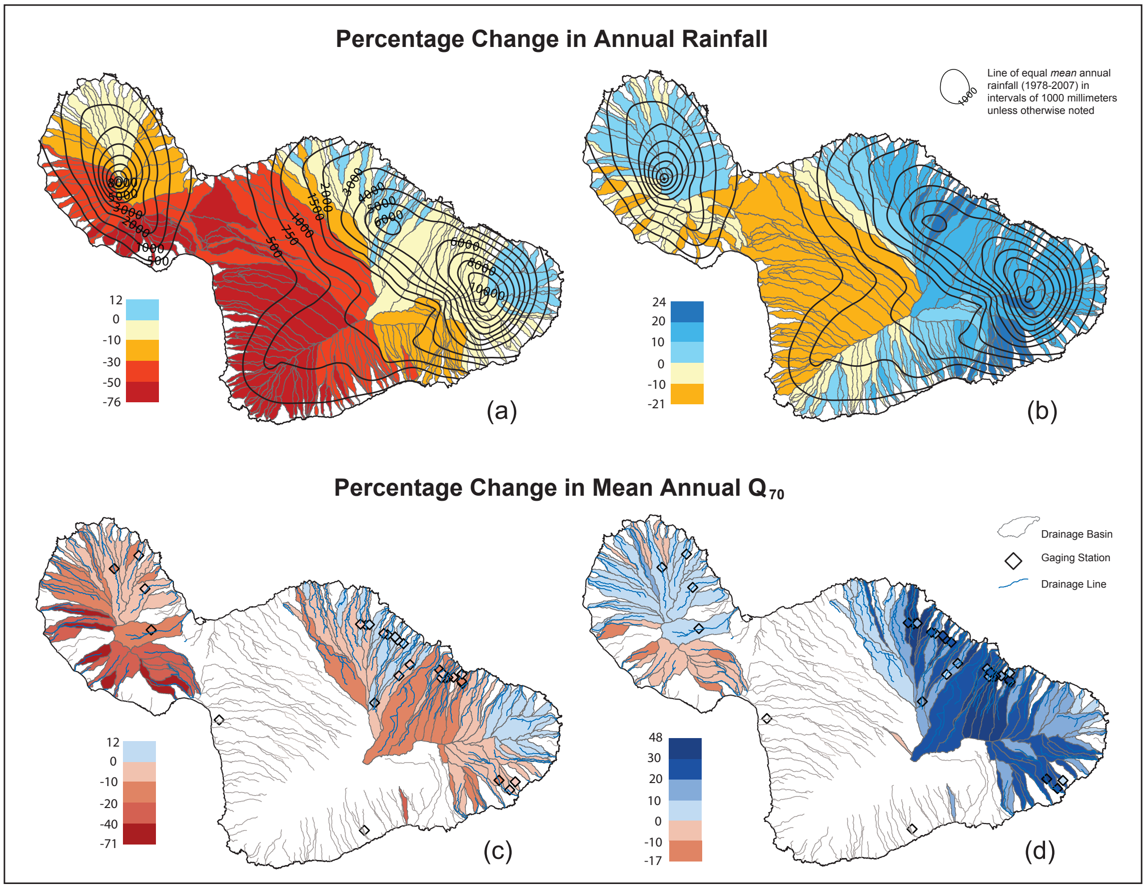

Figure 4. Case study of projected changes in rainfall on the island of Maui, Hawai‘i and associated estimates of changes in low flows. (a) Percentage change in average annual rainfall from statistical downscaling models (Timm et al., 2015) at ungaged basins between 1978-2007 and 2071-2099. (b) Percentage change in average annual rainfall from dynamical downscaling models (ADCP 2016) at ungaged basins between 1978-2007 and 2090-2109. (c) Percentage change in average annual Q_{70} associated with rainfall A computed using rainfall elasticity (ε) values from random-effects panel regressions for ungaged basins and from streamflow records for gaging stations. (d) Percentage change in average annual Q_{70} associated with rainfall B computed using elasticity values from random-effects panel regressions for ungaged basins and from streamflow records for gaged basins. Basins without an estimate of changes in low flow are classified as non-perennial and streams in these basins do not have natural low flows for recent conditions. Some ungaged streams may be misclassified.

7. ANALYSIS AND FINDINGS

In climate-change assessments, such as the application presented in this study, accuracy of MLR model coefficients is critical because the primary purpose of the MLR model is often to make inferences about streamflow under future rainfall conditions. Thus, the effects of multicollinearity and omitted-variable bias must be limited. This study developed low-flow regionalization models for the islands of Hawai‘i that can be used to assess low-flow response to annual rainfall variability. Given the limited available data and uncertainty in climate projections, simple models are appropriate to estimate low-flow duration discharges for future rainfall conditions. Panel regression was proposed as a robust framework to select MLRs with coefficients that can be interpreted for regional-scale climate-change assessments. Panel regression improved the regional estimates of rainfall elasticity compared to traditional model structures by reducing the negative effects of omitted-variable bias and multicollinearity. Panel regression distinguishes spatial and temporal variability in the data and accounts directly for both. Panel regression is particularly beneficial for situations in which flow heterogeneity exists within gaged streams, such as in Hawaiʻi. Panel regression in this study provided a means to utilize station data of different periods and lengths of record, which is advantageous for data-poor regions. Panel regression offers beneficial properties to synthesize multidimensional data, which is particularly relevant for investigating streamflow responses in a changing climate.

8. CONCLUSIONS AND RECOMMENDATIONS

Until uncertainty in downscaled climate projections is reduced, the developed models and their application on the island of Maui provide only a generalized spatial understanding of the sensitivity of low flows to changes in rainfall. A more spatially explicit understanding of groundwater/surface-water interactions and improved methods to classify streams in terms of their sensitivity to changes in climate would help to refine the regions of similar low-flow sensitivity to changes in rainfall proposed in this study. Plausible ranges of future changes in surface-water availability were estimated for the island of Maui, which should be useful to identify areas of concern and help develop adaptive-management strategies. Although data in this study did not indicate that rainfall elasticity is sensitive to average rainfall, the sensitivity of low flows to changes in rainfall between stream classes generally reflected basin recharge processes and may be affected in future climate conditions if groundwater storage is substantially altered. Further understanding of the temporal variability of rainfall elasticity in Hawaiʻi as a function of climatic variables is necessary to provide an improved understanding of past and future low-flow conditions. Limited availability of long-term data that cover the ranges of projected changes in climate is a major challenge to developing robust empirical models to assess future hydrologic conditions.

9. MANAGEMENT APPLICATIONS AND PRODUCTS

This study compared the panel-regression framework to traditional regression methods for estimating low flows and for quantifying the percentage change in low flows associated with a percentage change in rainfall (elasticity). Panel-regression methods were shown to provide a more robust understanding of the relation between streamflow and rainfall than traditional regression methods and can be applied in fields other than surface-water hydrology to assess climate-change impacts.

Climate projections for the Hawaiian Islands are highly uncertain and this uncertainty needs to be reduced if projections are to provide more actionable information to resource managers. To understand climate-change impacts on streamflow, this study mostly focused on studying the sensitivity of streamflow to changes in rainfall. The selected sensitivity approach utilizes a minimum level of complexity appropriate for regional climate-change impact assessments given the available data. The application of the sensitivity approach provided a spatial understanding of the vulnerability of different regions to changes in rainfall and low flows to resource managers. This understanding is critical to resource managers developing and prioritizing adaptive-management strategies for surface-water use and ecological considerations. Results of the case study on Maui indicated that flow and habitat in some streams are likely to decline for both climate projections. The sensitivity of East Maui streams to changes in rainfall was generally greater than for West Maui streams. Management prioritization must also consider the importance of each stream from ecologic, cultural, and irrigation standpoints.

10. OUTREACH

The scientific community in Hawai‘i was the main audience that was reached by this project through workshops and conferences. These meetings were beneficial for other scientists in Hawai‘i for the following key reasons:

- Limitations about using MLR models for assessing streamflow response to climate change were presented.
- A novel approach to develop MLR models with temporally varying explanatory variables using panel regression was proposed.
- Challenges of incorporating available climate projections in hydrologic models for the Hawaiian Islands were discussed.
- Results and methods were shared with academics studying climate-change effects on stream habitat.

The local water-management stakeholders including the State of Hawai‘i Commission on Water Resource Management, the City and County of Honolulu Board of Water Supply, and the State of Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources were made aware of potential impacts of projected changes in rainfall on low flows through webinar presentations.

Conference and workshop presentations:

Bassiouni M., 2016. Sensitivity of low lows to rainfall variability in ungaged Hawai‘i streams. A case study to estimate the effects of projected climate on surface-water availability and stream habitat on Maui, Hawai‘i. Climate Science Webinar Series, 1 April 2016.

Bassiouni M., 2015. Climate-change effects on low flows and habitat in Hawai‘i streams. Climate Science Webinar Series, 3 September 2015.

Bassiouni M., 2015. Climate-change effects on low flows and habitat in Hawai‘i streams. PICSC/PICCC Climate Science Symposium, Honolulu, 26-27 February 2015.

Bassiouni M., Regionalization of Low Flows in Hawai‘i Streams for Past and Future Rainfall Conditions. AGU Fall Meeting, San Francisco, CA, 15-19 December 2014.

Bassiouni M., Estimating climate-change impacts on low-flow discharges of Hawai‘i streams. Workshop on Regional Climate Change and Environmental Response in Hawai‘i, International Pacific Research Center, Honolulu HI, 23-24 July 2014.

Manuscript:

Bassiouni, M., Vogel, R. M. and Archfield, S. A. 2016. Panel regressions to estimate low-flow response to rainfall variability in ungaged basins. Water Resour. Res.. Accepted Author Manuscript. doi:10.1002/2016WR018718.

Project data and results:

Bassiouni, M., 2016, Summary drainage basin and low-flow characteristics in gaged Hawaii streams and summary rainfall projections for the late 21st century and associated changes in low flows and usable habitat for native stream fauna in gaged and ungaged Maui, HI streams: U.S. Geological Survey data release, http://dx.doi.org/10.5066/F7TH8JV3.

CITED REFERENCES

ADCP (2016), Hawaii regional climate model simulations (HRCM) website. Asia-Pacific Data-Research Center of the International Pacific Research Center, University of Hawaii at Manoa. Accessed at http://apdrc.soest.hawaii.edu/datadoc/hrcm.php on February 1, 2016.

Oki, D. S., R. H. Wolff, and J. A. Perreault (2010), Effects of surface-water diversion on streamflow, recharge, physical habitat, and temperature, Nā Wai ‘Ehā, Maui, Hawai‘i, U.S. Geological Survey Scientific Investigations Report 2010-5011, 154 p.

Timm, O. E., T. W. Giambelluca, and H. F. Diaz (2015), Statistical downscaling of rainfall changes in Hawai‘i based on the CMIP5 global model projections, J. Geophys. Res. Atmos., v. 120, no. 1, 2014JD022059, doi:10.1002/2014JD022059.